

Measurement of the $t\bar{t}$ production cross section at $\sqrt{s} = 1.96$ TeV in the lepton+jets channels with soft muon tag

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Abstract

A measurement of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at 1.96 TeV is presented. The soft-muon tagging technique is applied to e+jets and μ +jets candidate events selected in 94 pb^{-1} of data collected from August 2002 to July 2003. Seven candidate events are selected in the e+jets channel, and eight in the μ +jets channel, over backgrounds of 1.1 ± 0.9 and 2.2 ± 1.0 , respectively. The combined result for the $t\bar{t}$ production cross section is

$$(11.2 \pm 4.0 \text{ (stat)} \pm 1.3 \text{ (syst)} \pm 1.1 \text{ (lumi)}) \text{ pb.}$$

1 Introduction

In a lepton+jets final state arising from $t\bar{t}$ production, a b quark stems from the decay of each of the top quarks, and half of the time a c quark from the hadronic W decay. Taking into account the following branching ratios [1],

- 10.6% for $b \rightarrow \mu$,
- 8.0% for $b \rightarrow c \rightarrow \mu$,
- 9.8% for $c \rightarrow \mu$,

an average of 0.42 soft muons is expected to be present in every such event, hence the motivation for making use of soft-muon tagging in order to identify events from top production.

In this note, a measurement of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at 1.96 TeV is presented, where the soft-muon tagging technique is applied to the lepton+jets final states. The data sample was collected between August 2002 and July 2003, and reconstructed with RECO versions p13.05, p13.06 and r13.06.

The $t\bar{t}$ Monte Carlo samples used for this analysis were generated for a top quark mass of 175 GeV/ c^2 , using ALPGEN 1.1 with hadronization performed by PYTHIA. These events were processed with version mcp14.02 of the DØ simulation chain, and reconstructed with version p14.02 of RECO.

2 Event selection

2.1 Preselections

The preselections in the e+jets and μ +jets topologies follow closely those designed for the topological analyses described in Refs. [2, 3], but of course with removal of the soft-muon veto applied therein. Their main goal is to select a sample of events containing a leptonically decaying W. A brief account of the preselection criteria is given below.

The data sample used is composed of those good luminosity blocks also labelled as good in terms of missing E_T reconstruction [3], not belonging to bad quality runs with respect to the SMT, CFT, calorimeter and muon system, and belonging to the good run list established by the JetMET group. For unscaled triggers, this corresponds to an integrated luminosity of 94 pb $^{-1}$.

All the variables used in this analysis were determined using version v00-04-02-br of TopAnalyze [4].

2.1.1 Electron+jets

As in Ref. [2],

- the trigger condition is required to be EM15_2JT15;
- the primary vertex must fall within $|z| < 60$ cm, and have at least three tracks attached to it;

- a central electron must be found with $p_T > 20 \text{ GeV}/c$, matched to a charged track, and with Likelihood > 0.4 ;
- a veto on additional energetic electrons is applied;
- the missing E_T must exceed 20 GeV ;
- the azimuthal angle between the electron and missing E_T directions must be larger than 0.5 radians.

To obtain a sample of events with loosely identified electrons, the likelihood requirement is dropped.

2.1.2 Muon+jets

As in Ref. [3]

- the trigger condition is required to be MU_JT20_L2M0;
- the primary vertex must fall within $|z| < 60 \text{ cm}$, and have at least three tracks attached to it;
- an isolated global (*i.e.*, matched to a charged track) medium muon must be found, with $p_T > 20 \text{ GeV}/c$, $|\eta| < 2$ and DCA-significance < 3 ;
- the missing E_T must exceed 20 GeV .

The muon isolation is defined in two steps: a loose isolation, where the muon direction is required to be away from any jet direction by a ΔR of at least 0.5 ; a tight isolation, where it is required in addition that less than 2.5 GeV calorimetric energy be found in a hollow cone with inner and outer radii of 0.1 and 0.4 around the muon direction, and less than 2.5 GeV charged energy in a cone of radius 0.5 around the muon direction.

2.2 Topological cuts

In the data sample, 4306 and 4926 events are retained by the preselections in the e +jets and μ +jets channels, respectively. Topological criteria allow a further enrichment in signal events to be obtained.

Here and in the following, only jets satisfying the top group quality criteria [5], and with $E_T > 15 \text{ GeV}$ and $|\eta| < 2.5$ are considered. The jet energy is corrected with version 4.2 of the **JetCorr** package, including a specific correction in case of the presence of a muon in the jet.

A minimum of three jets is first required. The effect of this cut on the data and on simulated $t\bar{t}$ events is shown in Fig.1. In the data sample, 321 e +jets and 379 μ +jets events fulfil this requirement.

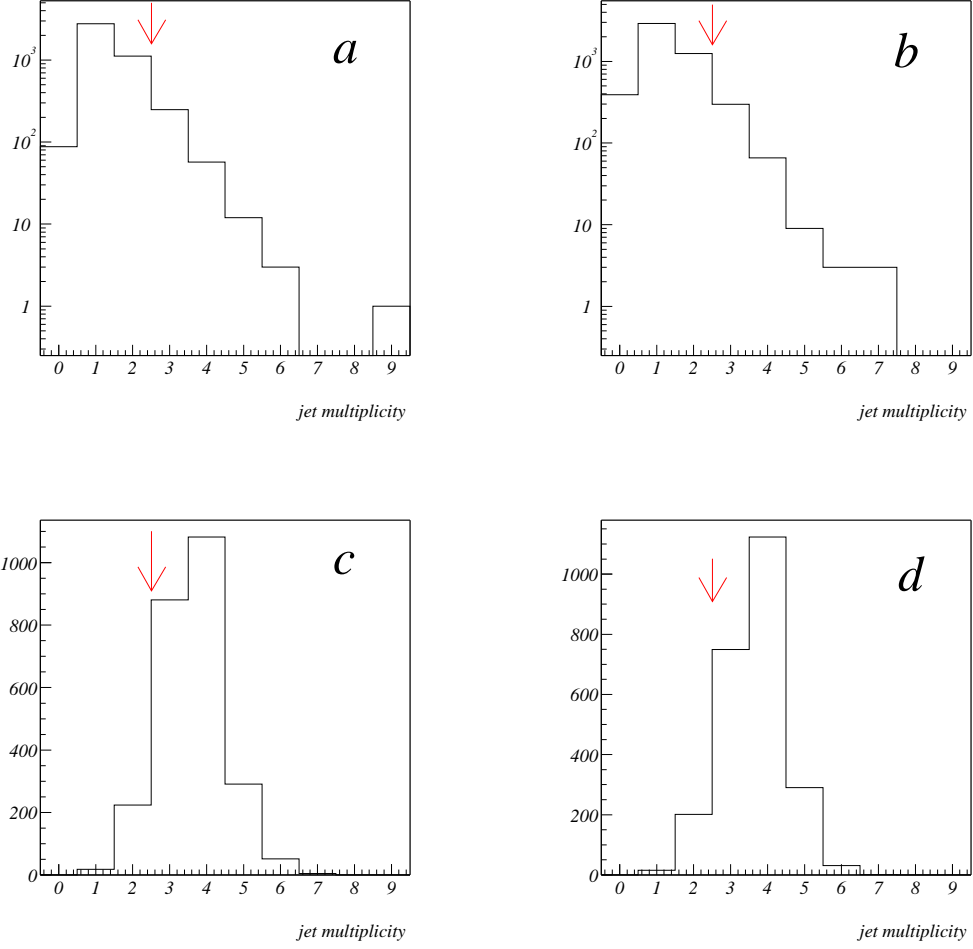


Figure 1: Jet multiplicity distributions in e +jets (a) and μ +jets (b) data events after preselection, and the corresponding distributions (c and d) for simulated signal events. The selection cut is indicated.

Additional topological cuts, inherited from Run I [6], are next applied:

- $H_T > 110 \text{ GeV}$, where H_T is the sum of the jet transverse energies;
- $\mathcal{A} > 0.04$, where the aplanarity \mathcal{A} is defined from the normalized momentum tensor constructed with the jet and W momenta.¹

The effect of these cuts on the data and on simulated $t\bar{t}$ events is shown in Fig. 2. In the data sample, 88 e+jets and 102 μ +jets events survive at this point.

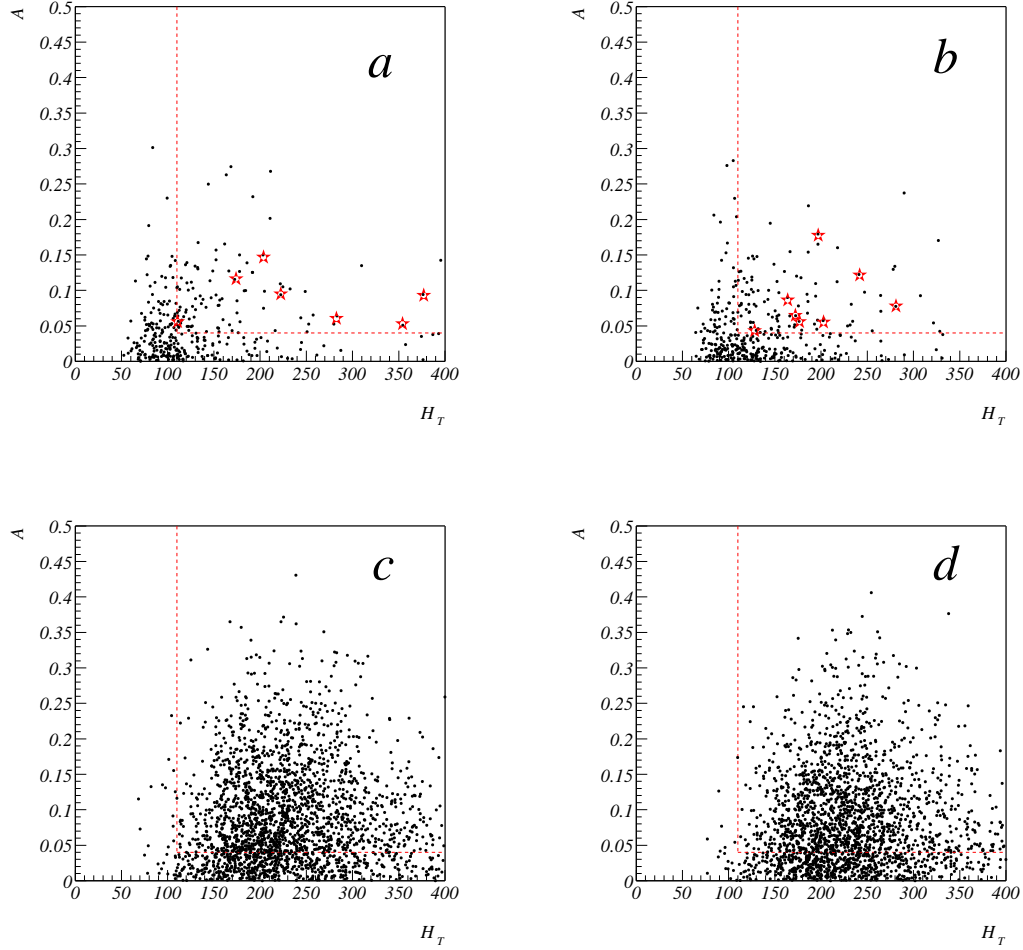


Figure 2: Distributions of \mathcal{A} vs. H_T in e+jets (a) and μ +jets (b) data events after the jet multiplicity cut, and the corresponding distributions (c and d) for simulated signal events. The selection cuts are indicated. In the data distributions, the events tagged by a soft muon are highlighted.

¹The W momentum is calculated from the lepton momentum and the missing E_T , imposing the W mass constraint. The solution with the lower neutrino longitudinal momentum is chosen.

2.3 Soft muon tagging

The last step in the data selection consists in the requirement that at least one jet be tagged by a soft muon. For a jet to be tagged, a medium muon with $p_T > 4 \text{ GeV}/c$ and $|\eta| < 2$ must be found within $\Delta R < 0.5$ of the jet direction. If the muon is matched to a central track with an association χ^2 smaller than 100, the kinematic parameters are taken from the track, as for isolated muons; otherwise, the local muon parameters are used. In the μ +jet channel, it is furthermore verified that the W-decay candidate muon is not used to tag a jet.

Seven events are tagged in the e+jets channel, and eight in the μ +jets channel (Table 1). They are shown highlighted in Fig. 2.

Table 1: Candidate events

| e+jets | | μ +jets | |
|--------|----------|-------------|----------|
| run | event | run | event |
| 164040 | 19265127 | 164213 | 78708013 |
| 166928 | 4207860 | 166317 | 36379090 |
| 167010 | 846729 | 169794 | 13431084 |
| 168136 | 2215240 | 175322 | 2093953 |
| 175515 | 11492464 | 175322 | 3728884 |
| 176875 | 16966764 | 175322 | 10511930 |
| 177243 | 22268032 | 175795 | 19319061 |
| | | 177312 | 10166327 |

3 Backgrounds

The main backgrounds arise from

- QCD multijet events in which a jet is wrongly identified as an electron or as an isolated muon,
- generic W+jets events.

These backgrounds are measured in the data.

In addition, the background from $(Z \rightarrow \mu\mu)$ +jets events, in which one of the muons is reconstructed inside a jet and at the same time there is substantial fake missing E_T , is estimated from Monte Carlo.

3.1 QCD background

The QCD background can be evaluated with the “Matrix method” [5] applied to the soft-muon tagged sample. The loose electron sample is obtained by relaxing the likelihood condition, and the loose muon sample by requiring only the loose isolation criterion. The loose e+jets sample contains ten events, and the loose μ +jets sample twelve events.

The signal and QCD background efficiencies have been determined in Refs.[2, 3]. For events containing at least three jets, the signal efficiencies are 0.792 ± 0.021 and 0.898 ± 0.005 for electrons and for muons, respectively. The corresponding background efficiencies are 0.207 ± 0.013 and 0.116 ± 0.013 . As a result, the QCD backgrounds in the e+jets and μ +jets tagged samples amount to 0.33 ± 0.53 and 0.53 ± 0.60 events, respectively.

An alternative method can be considered to evaluate the QCD background. This background is first calculated in the untagged sample, again using the matrix method. With samples of 209 (228) loosely identified electrons (loosely isolated muons), the QCD background in the untagged sample amounts to 27.4 ± 4.0 and 27.8 ± 4.1 events in the e+jets and μ +jets channels, respectively.

To predict the corresponding amounts in the tagged sample, the probability for a QCD multijet event to contain a soft muon has to be evaluated. To this end, a jet tagging probability density (or “tag rate function”) was determined as a function of jet p_T , η_{det} and φ , using a sample of QCD events containing at least four jets. (These events were triggered by the 4JT10 condition, and satisfy $H_T > 100$ GeV.) The resulting tag rate functions are displayed in Fig. 3. The p_T dependance is related to the probability for a muon to be reconstructed with a transverse momentum larger than $4 \text{ GeV}/c$. The $|\eta_{det}|$ dependance is due to the $|\eta|$ cut applied to the muons, and the φ dependance reflects the geometrical acceptance of the muon detector.

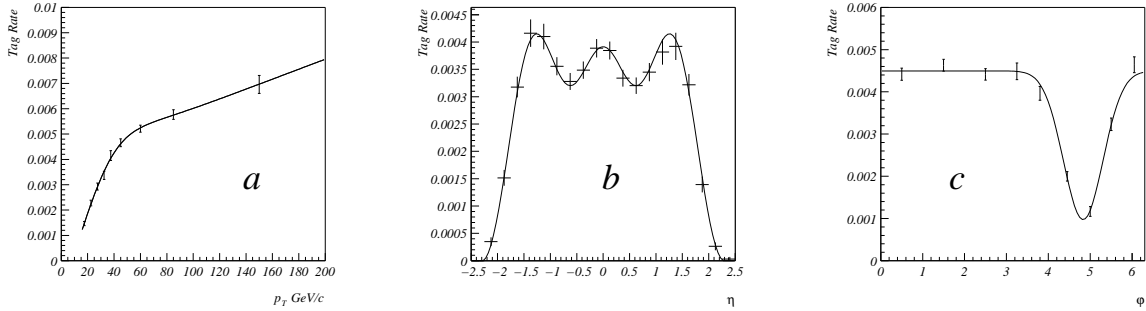


Figure 3: Tag rate functions, *i.e.*, probabilities for a jet to be tagged by a soft muon, as a function of the jet p_T (a), η_{det} (b) and φ (c).

The average event tag rate for the QCD background in the untagged sample is approximated by the sum of the individual jet tag rates, divided by the total number of events. While this should be a fairly good approximation for the e+jets channel, it is unlikely to be the case for μ +jets. The reason is that in the latter channel, because of the presence of an isolated muon, the untagged sample is enriched in heavy flavours compared to the QCD multijet sample used to determine the tag rate functions. This alternative method for the evaluation of the QCD background is therefore pursued only for the e+jets channel. The average event tag rate is 0.016, and hence the expected QCD background in the tagged sample is 0.44 ± 0.06 . This estimate, which is in good agreement with the value of 0.33 ± 0.53 determined within the tagged sample, will be used in the following because of its superior precision.

3.2 W+jets background

The background from W+jets is also obtained by applying an event tagging probability to the samples of 88 e+jets and 102 μ +jets untagged events, after QCD background subtraction performed as indicated above. There are 60.6 ± 4.0 and 74.2 ± 4.1 untagged W+jets events in the electron and muon + jets channels, respectively.

These W+jets untagged events however contain a contribution from top events which has to be first subtracted.² The QCD-background-subtracted inclusive jet multiplicity is shown in Fig. 4 before topological cuts, after correction for the trigger biases performed as in Refs. [2, 3]. The true W+jets component is assumed to satisfy Berends scaling, *i.e.*, it is parametrized as $N_i = \alpha^{(i-3)} N_3$, where N_i is the number of W+jets events with jet multiplicity $\geq i$. The top contribution in the i^{th} bin is $f_i N_{\text{top}}$, where N_{top} is the total number of top events at this stage of the analysis and f_i is the fraction of top events with at least i jets. These fractions are determined from Monte Carlo. A fit to the data, shown in Fig. 4, allows α , N_3 and N_{top} to be determined. The value of interest, namely $f_3 N_{\text{top}}$ needs furthermore to be corrected for the efficiency of the topological cuts, 71% as determined by Monte Carlo. (The effect of the trigger bias is negligible for top events after topological cuts.) The result is that the untagged W+jets samples contain 18.9 ± 56.0 and -8.3 ± 43.4 top events in the e+jets and μ +jets channels, respectively.

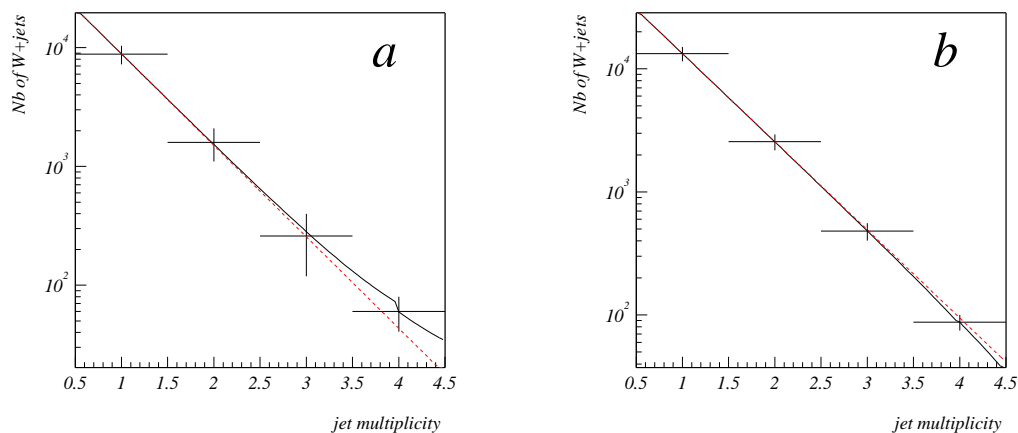


Figure 4: For the e+jets (a) and μ +jets (b) channels, distribution of the inclusive jet multiplicity for W+jets events, after QCD background subtraction and trigger bias correction. The result of the fit discussed in the text is also shown as a full curve with the top contribution included, and as a dashed curve without the top contribution.

Monte Carlo studies with full simulation indicate that, in the QCD multijet sample, about half of the tagging muons are due to in-flight decays, and the other half to heavy flavour decays. A comparison between the heavy flavour content of multijet events gener-

²The method used in Ref. [5] to determine the W+jets background in the tagged sample introduces a strong correlation between signal and background estimates, and renders delicate the combination of the results with those of other channels.

ated by PYTHIA with that of W+jets events generated by ALPGEN³ was performed, and it was found that those heavy flavour contents (defined as the rate of production of muons with $p_T > 4 \text{ GeV}/c$ originating from b- or c-hadron decays) are very similar. Therefore, the tag rate functions determined in multijet events have not been modified for W+jets events; they are however affected by a relative systematic error of 20% due to the limited statistics of the ALPGEN sample used for this study. The resulting average event tag rate for the untagged W+jets events is thus 0.016 ± 0.003 , leading to expected numbers of tagged events from this source $N_{W+jets} = 0.67 \pm 0.92$ and 1.31 ± 0.74 in the e+jets and μ +jets channels, respectively.

3.3 $Z \rightarrow \mu\mu$ background

The ALPGEN generator was used to simulate $Z \rightarrow \mu\mu$ events with at least two jets [8]. These events were subjected to the same analysis procedure as the data. Possible deficiencies in the simulated jet multiplicity are covered by a systematic error of 5%. In addition, a systematic error of $\pm 30\%$ was conservatively estimated, equivalent to a variation of $\pm 20\%$ on the scale of the missing E_T (*i.e.*, $\pm 4 \text{ GeV}$ at the cut value of 20 GeV). In the end, the number of background events expected from this source turns out to be 0.33 ± 0.15 .

3.4 Total background

The sums of the QCD, W+jets and Z+jets backgrounds amount to 1.12 ± 0.92 and 2.18 ± 0.97 events in the e+jets and μ +jets channels, respectively. The observation of seven and eight events in those channels therefore unambiguously implies the presence of a signal in the data.

4 Signal efficiency

The trigger and preselection efficiencies have been determined according to the studies reported in Refs. [2, 3].

The reduction of the trigger efficiencies due to the lower jet multiplicity requirement in the soft-muon tag analyses compared to the topological ones (*i.e.*, a minimum of three, rather than four jets) is negligible. On the other hand, the trigger efficiency is higher in the μ +jets channel, due to the possibility for the tagging muon to fulfil the trigger condition. The muon trigger efficiency was found to be constant with p_T down to $7 \text{ GeV}/c$, with a slight reduction of up to 3% as the muon p_T decreases to $4 \text{ GeV}/c$ [9]. Altogether, the trigger efficiencies are $(93.0 \pm 2.2)\%$ in the e+jets channel, and $(98.2 \pm 0.4)\%$ in the μ +jets channel.

The preselection efficiencies are $(25.0 \pm 1.5)\%$ in the e+jets channel, and $(34.8 \pm 2.6)\%$ in the μ +jets channel.

The efficiencies of the jet multiplicity cut and of the additional topological criteria are $(90.5 \pm 0.6)\%$ and $(72.0 \pm 0.9)\%$ in the e+jets channel, respectively, and $(91.0 \pm 0.6)\%$ and

³A detailed account of the heavy flavour content in W+jets final states, as a function of the jet multiplicity, is reported in Ref. [7].

(69.8 ± 1.0)% in the μ +jets channel. The relative systematic errors due to jet identification, energy scale and resolution are $\pm 2.9\%$, $^{+0}_{-2}\%$ and $\pm 1\%$, respectively.

The efficiencies of the muon tag for signal events are (19.8 ± 1.0)% in the e+jets channel and (19.6 ± 1.1)% in the μ +jets channel. They were determined by rescaling the muon tag probability in the $t\bar{t}$ Monte Carlo by 1.11 ± 0.05 , the ratio of local muon reconstruction efficiencies in the data and in the Monte Carlo. This correction factor was obtained from muons in the J/ψ peak identified by the MTC method. The error on the muon tag efficiency is dominated by the limited statistics of the J/ψ samples. The muon tag rate is furthermore affected by a relative systematic error of 3% to account for uncertainties in the semileptonic branching ratios and in the modelling of the muon spectrum in b and c-hadron decays.

All the above efficiencies were determined for the lepton+jets channels, assuming that the lepton is emitted directly in a W decay. An additional contribution to the signal however comes from the cascade decays $W \rightarrow \tau \rightarrow \ell$ ($\ell = e$ or μ). This is treated as a correction factor to the efficiency, which amounts to 1.040 ± 0.014 in the e+jets channel, and to 1.044 ± 0.014 in the μ +jets channel.

Finally, the selection efficiencies are also affected by the assumed top mass value. A variation of $\pm 5 \text{ GeV}/c^2$ induces a relative efficiency variation of $\pm 6\%$ which is treated as a systematic error.

The overall efficiencies in the e+jets and μ +jets channels are therefore ($3.1 \pm 0.3 \pm 0.3$)% and ($4.5 \pm 0.4 \pm 0.4$)%, respectively, where the first error is uncorrelated between the two channels, while the second is fully correlated.

A summary of all systematic errors (including Monte Carlo statistics) is given in Table 2.

Table 2: Summary of relative errors on the signal efficiencies, in percents

| | e+jets | μ +jets | correlated |
|------------------|--------|-------------|------------|
| Trigger | 2.4 | 0.4 | |
| Preselection | 6.2 | 7.5 | 2.0 |
| Topological cuts | 1.4 | 1.5 | 3.5 |
| Soft muon tag | 5.3 | 5.5 | 4.5 |
| b/c decay model | | | 3.0 |
| Tau correction | 1.3 | 1.3 | |
| Top mass | | | 6.0 |

Assuming a $t\bar{t}$ production cross section of 7 pb, and taking into account the W decay branching ratio of (10.7 ± 0.1)% per lepton flavour [10] and the integrated luminosity of (94 ± 9) pb^{-1} (reduced to 92 pb^{-1} in the e+jets channel because of a few runs in which the EM15_2JT15 trigger was prescaled), the numbers of signal events expected are (2.91 ± 0.47) and (4.25 ± 0.71) in the e+jets and μ +jets channels, respectively.

5 Production cross section

In the e+jets channel, seven events are selected over a total background of 1.12 ± 0.92 . The corresponding numbers in the μ +jets channel are eight and 2.18 ± 0.97 . As a result, the $t\bar{t}$ production cross section is measured to be (14.1 ± 7.1) pb and (9.6 ± 5.2) pb in those two channels, respectively. This information is summarized in Table 3.

Table 3: Contributions to the cross section measurements in the two individual channels.

| | \mathcal{L} (pb ⁻¹) | Signal efficiency | Signal expected (for $\sigma_{t\bar{t}} = 7$ pb) | Background | Observed events | $\sigma_{t\bar{t}}$ (pb) |
|-------------|-----------------------------------|-------------------|---|---------------|-----------------|--------------------------|
| e+jets | 92 ± 9 | $(3.1 \pm 0.4)\%$ | 2.9 ± 0.5 | 1.1 ± 0.9 | 7 | 14.1 ± 7.1 |
| μ +jets | 94 ± 9 | $(4.5 \pm 0.6)\%$ | 4.2 ± 0.7 | 2.2 ± 1.0 | 8 | 9.6 ± 5.2 |

Taking the correlated errors into account, the combined result is⁴

$$(11.2 \pm 4.0 \pm 1.3 \pm 1.1) \text{ pb}$$

where the first error is statistical, the second one is systematic, and the third one is due to the luminosity uncertainty.

Acknowledgements

We wish to thank Markus Klute and Lukas Phaf for the fruitful and pleasant collaboration.

⁴The two channels are weighted by their statistical and uncorrelated systematic errors. The statistical errors on the backgrounds are included in the final overall statistical error.

References

- [1] D. Abbaneo *et al.*, “*A combination of preliminary electroweak measurements and constraints on the standard model*”, CERN-EP/2001-21.
- [2] Lukas Phaf and Ia Iashvili, “*Measurement of the $t\bar{t}$ cross section at $\sqrt{s} = 1.96\text{ TeV}$ in the $e+\text{jets}$ channel*”, DØ Note 4194.
- [3] Markus Klute, “*Measurement of the $t\bar{t}$ cross section at $\sqrt{s} = 1.96\text{ TeV}$ in $\mu\text{-plus-jets}$ events*”, DØ Note 4185.
- [4] M. Klute, L. Phaf and D. Whiteson, “*TopAnalyze - A framework Analyze Package for Top group Analyses*”, DØ Note 4122.
- [5] S. Anderson *et al.*, “*Measurement of the $t\bar{t}$ cross section at $\sqrt{s} = 1.96\text{ TeV}$* ”, DØ Note 4116.
- [6] The DØ Collaboration, “ *$t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8\text{ TeV}$* ”, Phys. Rev. D67 012004 (2003).
- [7] R. Demina *et al.*, “*Measurement of the $t\bar{t}$ production cross section at $\sqrt{s} = 1.96\text{ TeV}$ using lifetime tagging*”, DØ Note 4141.
- [8] S. Anderson *et al.*, “*Toward a measurement of the $t\bar{t}$ cross section at $\sqrt{s} = 1.96\text{ TeV}$ using dimuon events*”, DØ Note 4200.
- [9] M. Agelou, private communication
- [10] Particle Data Group, <http://pdg.lbl.gov/2003/s043.pdf>